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Muon Colliders: A Vision for the Future of Fermilab

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Muon Colliders: A vision for the future of Fermilab

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Abstract

We describe a "vision" of the future of the accelerator complex at Fermilab in which the present facilities are enhanced with the addition of a muon storage ring neutrino source (Step 1), followed by the first muon collider (Step 2), and finally a site–filling 4 TeV muon collider (Step 3). For each step we describe the required facility upgrade, siting issues, the evolution of the physics program, and a very speculative aggressive strawman schedule.

1 Introduction

At present the long–term evolution of the accelerator complex at Fermilab is undecided. The possible options currently seem to be (a) A very large hadron collider (VLHC), (b) The next linear e^+e^- collider (NLC), or (c) A high–luminosity multi–TeV muon collider. We can anticipate a debate on which of these long term options for the laboratory (if any) is the right one. To focus the coming muon collider part of the debate, it is useful to have a concrete vision of how the facilities and the associated physics program at Fermilab would evolve in a muon collider scenario. In this note we describe a vision of the evolution of the existing Fermilab accelerator complex and associated physics program towards a site–filling 2×2 TeV Muon Collider. Although our vision is necessarily blurred at this early stage, we hope that this document will contribute to a discussion that leads to a clearer picture of the long term possibilities.

In formulating a muon collider staging scenario, we begin with the conclusions from the workshop [1] on "Physics at the First Muon Collider and Front–end of a Muon Collider" that was held at Fermilab in November 1997. This workshop surveyed the physics that could be done at Fermilab using the accelerator complex at the "front–end" of a muon collider, and considered the physics potential of the first muon collider (FMC). Three basic workshop conclusions were:

(i) Of the various possible physics programs that could be pursued with the accelerator complex at the front end of a muon collider, the most attractive appears to be the neutrino physics program, which includes neutrino oscillation physics using muon storage ring neutrino sources [2], and high energy neutrino physics using the beams that are unavoidably produced downstream of the straight sections within the muon acceleration system [3] and within the collider ring.

(ii) There are several possible choices for the energy, and hence physics program, of the FMC. If a Higgs–like boson is discovered with a mass less than twice the W mass, and no other new particles have been discovered, then an s–channel Higgs factory seems to be the natural choice for an FMC. This would be a unique physics facility. If other more interesting new particles have been discovered, then a higher energy (up to $\sim$ 500 GeV center–of–mass energy) FMC might be more desirable.

(iii) The ultimate muon collider goal is to provide a way of producing high luminosity lepton–antilepton collisions at the multi–TeV energy scale.

Based on these conclusions, we believe that a three step accelerator upgrade scenario is natural :

Step 1: A Muon Storage Ring Neutrino Source.

The 8 GeV proton Booster is upgraded to 16 GeV and located in a new beam enclosure. An intense muon source is constructed, together with a muon acceleration system and an $\sim$ 10 GeV muon storage ring neutrino source.

Step 2: The First Muon Collider (FMC).

The 400 MeV proton linac energy is upgraded to 1 GeV, a 3 GeV Pre-booster is built, and the muon source is upgraded. A muon accelerator is constructed together with the FMC. We imagine that the center–of–mass energy of the FMC will be in the range from 100 GeV to 500 GeV, and will be chosen to optimize the physics program.

Step 3: A Multi–TeV Muon Collider.

A site-filling $\sim$ 2 TeV muon acceleration system is built together with a 4 TeV muon collider, re-capturing the energy frontier at Fermilab.

This document is organized as follows. In Section 2, 3, and 4 we discuss respectively Steps 1, 2, and 3. For each step we describe the facility upgrade, siting issues, the evolution of the physics program, and a very speculative aggressive strawman schedule. In Section 5 we present a summary and some conclusions.

2 Step 1: Protons, Muons, and Neutrinos

In the first step towards a high energy muon collider, a muon storage ring neutrino source is constructed. This will facilitate the next generation of neutrino experiments beyond the currently approved program, provide an intense muon R&D facility for muon collider design studies, and offer some optional additional physics facilities (intense stopped muons, stopped pions, intense low energy kaons).

2.1 Step 1: Facility Upgrade

Figure 1 shows a schematic of the components needed for a muon storage ring neutrino source [6, 7]. The Step 1 facility upgrade consists of upgrading the proton source, adding an intense muon source and an intense neutrino source. The muon source will require a pion production target and capture system, a pion decay channel, and a muon cooling channel. The neutrino source will require a muon acceleration system, and a muon storage ring.

2.1.1 The Proton Source Upgrade

A 1997 summer study [4] explored the possibility of upgrading the existing proton source at Fermilab so that it can deliver the very short intense proton bunches needed at the front end of a muon collider. The overall upgrade would consist of upgrading the 400 MeV Linac energy to 1 GeV, upgrading the Booster energy to 16 GeV with the new Booster located in a new beam enclosure to overcome radiation limitations, and adding a 3 GeV Pre-booster to enable the protons to be compressed into short ($\sim$ 2 ns) long bunches. The proton source upgrade is

Table 1: Evolution of the proton source parameters in the scenario described in the text. The table is derived from Ref. [4] updated to reflect current thinking [5]. Phase 1 assumes a new 16 GeV Booster and a modest upgrade of the 400 MeV Linac to double the pulse length. Phase 0 is scaled from phase 1. In phase 2 the Linac energy is upgraded and a 3 GeV Pre-booster added. ($\star$) Recent thinking revises this number to 2.0×10^{12}

	Phase 0	Phase 1	Phase 2
Linac (operating at 15 Hz)			
Kinetic Energy (MeV)	400	400	1000
Current (mA)	50	50	65
Pulse Length (μs)	100	100	300
H^- per pulse	3×10^{13}	3×10^{13}	1×10^{14}
Pre–booster (operating at 15 Hz)			
Extraction Kinetic Energy (GeV)			3.0
Circumference (m)			158
Protons per bunch			2.5×10^{13}
Number of bunches			4
Transverse Emittance (mm–mr)			200π
Longitudinal Emittance (eV-sec)			1.5
Booster (operating at 15 Hz)			
Extraction Kinetic Energy (GeV)	16	16	16
Circumference (m)	474.2	474.2	474.2
Protons per bunch	3.6×10^{11}	$2.5^{(\star)} \times 10^{12}$	2.5×10^{13}
Number of bunches	84	12	4
Extracted bunch length σ_t (ns)	3	2 – 10	2
Transverse Emittance (mm–mr)	40π	50π	200π
Longitudinal Emittance (eV-sec)	0.4	0.2	2.0
Target Beam Power (MW)		1.2	3.8

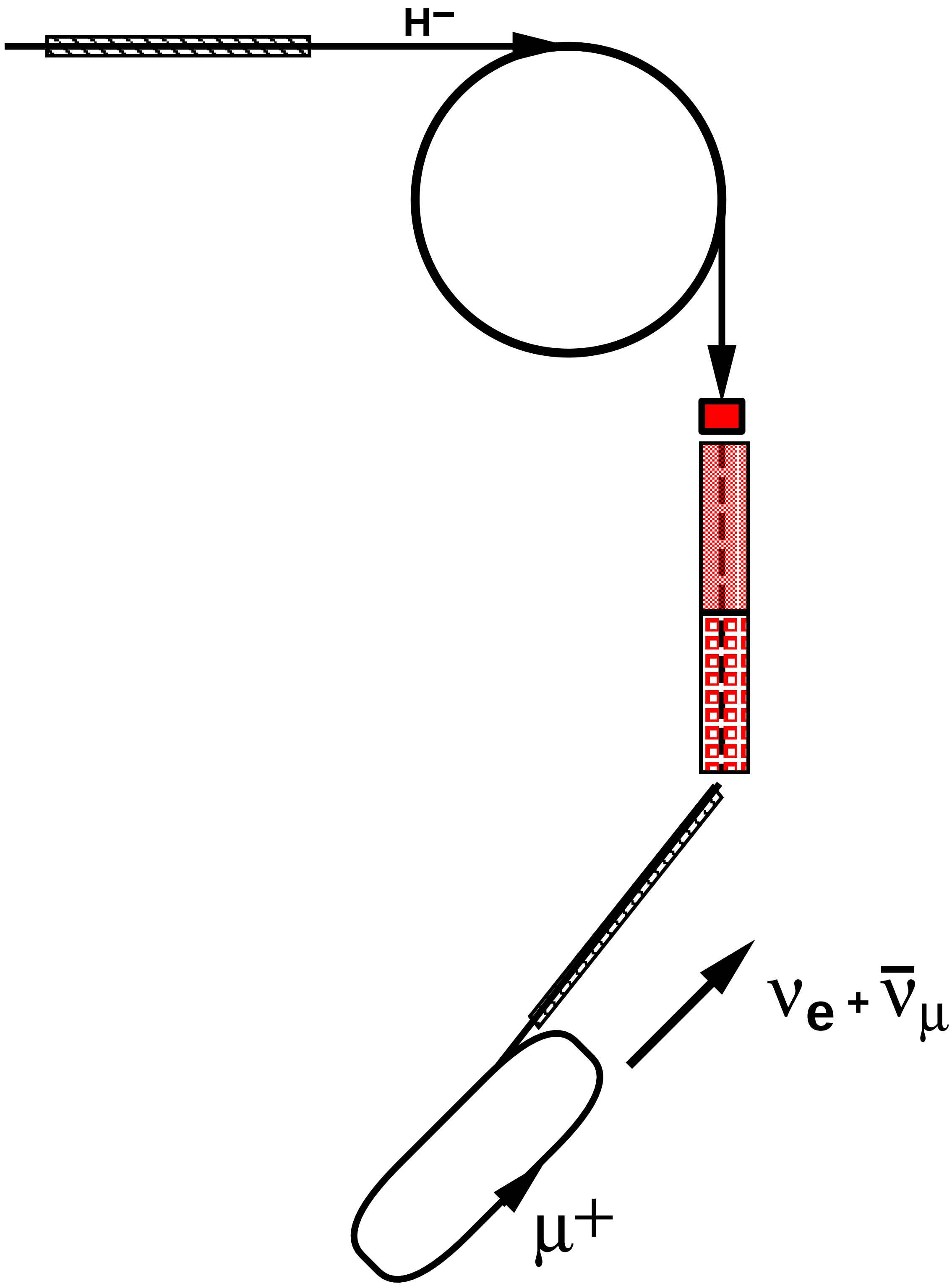

Figure 1: Schematic of the muon production, decay channel, cooling channel, acceleration linac, and muon storage ring system discussed in the text.

stagable. Of the staging scenarios described in [4] we will choose the one shown in Table 1, with phase 1 of the proton driver upgrade becoming part of the Step 1 facility upgrade, and phase 2 of the proton driver upgrade delayed until later. Hence, in Step 1 only the Booster is upgraded. The resulting proton source cycles at 15 Hz, and delivers 12 bunches per cycle, each containing 2.5×10^{12} protons at 16 GeV. In an operational year (10^7 secs) 4.5×10^{21} protons will be available for the pion production target.

After the proton source is upgraded there may be a period, before operation of the new muon storage ring neutrino source begins, when the new proton source is used to feed the Main Injector (MI) and hence enhance the ongoing Fermilab physics program. In Table 1 we refer to this period as "Phase 0", and summarize the anticipated enhanced performance of the MI. Note that up to five times more protons per minute could be available for acceleration in the MI than could be provided by any reasonable upgrades to the original 8 GeV Booster. The feasibility of accelerating a factor of five more protons in the MI is analyzed in Ref. [9] where it is found to be possible with modest MI upgrades. The Antiproton Source would also probably need upgrades (in the targetry, for instance) to take advantage of the increased intensity.

2.1.2 The Muon Source and Acceleration

In our vision of the Step 1 facilities at Fermilab, we will adopt the muon source and acceleration scheme described in Refs. [6, 7], summarized in Table 2, and discussed in the following paragraphs.

We begin by considering the pion production target. The proton beam power for the Step 1 source is ~ 1.2 MW. Although large, this is only 30% of the beam power needed for a high luminosity muon collider [5]. Hence, the Step 1 upgrade would be able to exploit the target technology being developed for a muon collider, and would offer the possibility of constructing, testing, and operating a less demanding version of the target required for the FMC. The current muon collider target concept consists of using a liquid metal jet injected into a 20 T solenoid. The high–field solenoid captures almost all of the charged pions that are produced in the downstream direction.

The 16 GeV protons interact in the target to produce, per incident proton, approximately 0.6 charged pions of each sign captured within the solenoidal channel. To collect as many pions as possible within a useful energy interval, it is proposed to use rf cavities to accelerate the lower energy particles and decelerate the higher energy particles. Muons are produced when the pions decay. At the end of a 50 m long decay channel [5], consisting of a 1.25 T solenoid, on average 0.2 muons of each charge would be produced for each proton incident on the pion production target. Hence, in each accelerator cycle the Step 1 muon source would produce 6×10^{12} muons of the desired charge at the end of the decay channel. In an operational year (10^7 secs) about 9×10^{20} muons would be produced in the

Table 2: Muon source parameters and acceleration parameters for a muon storage ring neutrino source at Fermilab, described in Refs. [6, 7]. The phase 1 proton source upgrade shown in Table 1 is assumed. The accelerator complex cycles at 15 Hz.

Pion Target	
π^- bunches per cycle	12
π^- captured per proton	0.6
π^- captured per year (10^7 secs)	2.8×10^{21}
Decay Channel	
μ^- bunches per cycle	12
μ^- captured per proton	0.2
μ^- captured per year (10^7 secs)	9×10^{20}
Mean muon energy (E)	250 MeV
Energy spread (σ_E/E)	0.15
Bunch length (σ_z)	1.5 m
Transverse Emittance (ϵ_N)	0.017 m-rad
Cooling Channel	
Cooled μ^- bunches per cycle	12
μ^- cooled per proton	0.3
μ^- cooled per year (10^7 secs)	8.1×10^{20}
Mean muon energy (E)	230 MeV
Energy spread (σ_E/E)	0.20
Bunch length (σ_z)	2 m
Transverse Emittance (ϵ_N)	0.005 m-rad
Acceleration	
μ^- bunches per cycle	$16 \times 12 = 192$
μ^- accelerated per year (10^7 secs)	4.7×10^{20}
Mean muon energy (E)	10 GeV
Energy spread (σ_E/E)	0.004
Bunch length (σ_z)	1 cm

decay channel and collected.

Simulations of the muon source described above have been made as a part of the muon collider feasibility studies being pursued by the muon collider collaboration [5]. The simulations predict that the muons exiting the decay channel would be captured within bunches with rms lengths $\sigma_Z = 1.5$ m, would have a mean energy of 250 MeV ($p_\mu = 227$ MeV/c), an energy spread $\sigma_E/E \sim 15\%$, and would populate a very diffuse transverse phase space corresponding to a normalized transverse emittance $\epsilon_N \sim 0.017$ m-rad. The transverse emittance is too large to fit within the acceptance of an acceleration and storage ring system. Hence in Fig. 1, to reduce ϵ_N by a factor of a few, downstream of the decay channel there is an ionization cooling channel of the type that is being developed by the MUCOOL collaboration [8]. The cooling channel would be ~ 150 m long, and would consist of 15 cells which use a high–field solenoid channel to keep the beam confined radially. The solenoids initially provide a field of 1.2 T, increasing down the channel to about 3 T at the end of the channel. The beam loss within the cooling channel is calculated to be about 10%. At the end of the cooling channel there would be about 5.4×10^{12} muons of the desired charge available per accelerator cycle, contained within 12 bunches, each with rms lengths $\sigma_Z \sim 2$ m, a mean energy of 230 MeV, an energy spread $\sigma_E/E \sim 20\%$, and a normalized transverse emittance $\epsilon_N \sim 0.005$ m-rad. Hence, there would be 8.1×10^{20} cooled muons per operational year.

Downstream of the cooling channel, the scheme described in Refs. [6, 7] uses a two–stage 805 MHz rf system to capture and accelerate muons from a long bunch with a broad energy distribution into 16 stable bunches with an inter-bunch spacing of ~ 0.375 m. The first stage consists of a 140 m long linac with $V_{rf} = 15$ MV/m and a central accelerating phase $\phi_s = 30°$. This stage captures the muons exiting the cooling channel, and provides the initial acceleration up to an energy $E_\mu = 1$ GeV. To keep the beam confined transversely, this first accelerating stage would consist of a string of rf cavities within a 5 T solenoid channel. The second acceleration stage described in Refs. [6, 7] consists of a 500 m long linac with $V_{rf} = 20$ MV/m and $\phi_s = 60°$. In principle this second stage could use a recirculating linear accelerator (RLA) rather than a straight linac. In Refs. [6, 7] the second stage accelerates the muon bunches to 10 GeV, and uses a quadrupole channel with a FODO lattice to provide transverse focusing. Approximately 60% of the muons exiting the cooling channel are expected to be captured within the rf buckets of the linac, and accelerated to 10 GeV. The final bunch lengths are given by $\sigma_z \sim 1$ cm, and the rms energy spreads are given by $\sigma_E/E \sim 4\%$. At the end of the last acceleration stage there are 4.7×10^{20} muons per operational year.

Table 3: Directions (dip and heading), baseline lengths (L), and the elevation change from the the center of one arc to the center of the opposite arc (Δx), listed for some interesting far sites for long baseline neutrino oscillation experiments. Numbers from Ref. [10].

	L (km)	Dip (Degrees)	Heading (Degrees)	Δx (feet)
Fermilab $\rightarrow$ Soudan	732	3	336	34
Fermilab $\rightarrow$ Gran Sasso	7332	35	50	370
Fermilab $\rightarrow$ Kamioka	9263	47	325	470

2.1.3 The Muon Storage Ring Neutrino Source

The muon storage ring needed to create an intense neutrino beam consists of two long straight sections connected together by two arcs. One of the straight sections is used for injection and extraction to a beam dump. The other straight section provides the neutrino beam, and must therefore point in the appropriate direction. It is desirable that the straight sections are long and the arcs are compact, so that a large fraction of the muons circulating in the storage ring decay within the neutrino beam–forming straight section. In our vision of the Step 1 facilities, we will adopt the design described in Refs. [6, 7] for a 10 GeV storage ring with a circumference of 448 m, and 150 m long straight sections. Hence, about one third of the muons decay whilst traveling in the desired direction, and there are 1.6×10^{20} muon decays per operational year within the neutrino beam–forming straight section of the storage ring.

2.2 Step 1: Siting Issues

Figure 2 and photograph 1 (attached at the end of the document) show the accelerator enclosures needed for Step 1. The sizes of the proton source enclosures are taken from Fig. III.1 of Ref. [4]. The 16 GeV Booster is located as close as is reasonable upstream of the Main Injector injection point. Note that the present design of the proton beam transport to MiniBooNE allows for an upgrade to enable the transport of 16 GeV beam, and also allows for a switch to send beam to an area other than MiniBooNE, which we take to be the target station for the Step 1 muon source. The new Booster is fed by the currently existing 400 MeV Linac using the MI8 beam enclosure with a new beam transport. The beam enclosures for the new Proton Source would be constructed by cut and fill. Downstream of the target hall and decay channel, the muon cooling channel is shown within a single 50 m long building. It might not be technically possible to lay out the 150 m long cooling channel in a 50 m long building, but without a detailed cooling channel design one cannot discard this approach. Following the cooling channel, a linac is shown which accelerates the muons to 1 GeV, followed by a recirculating linac (RLA) to accelerate the muons to 10 GeV. Note

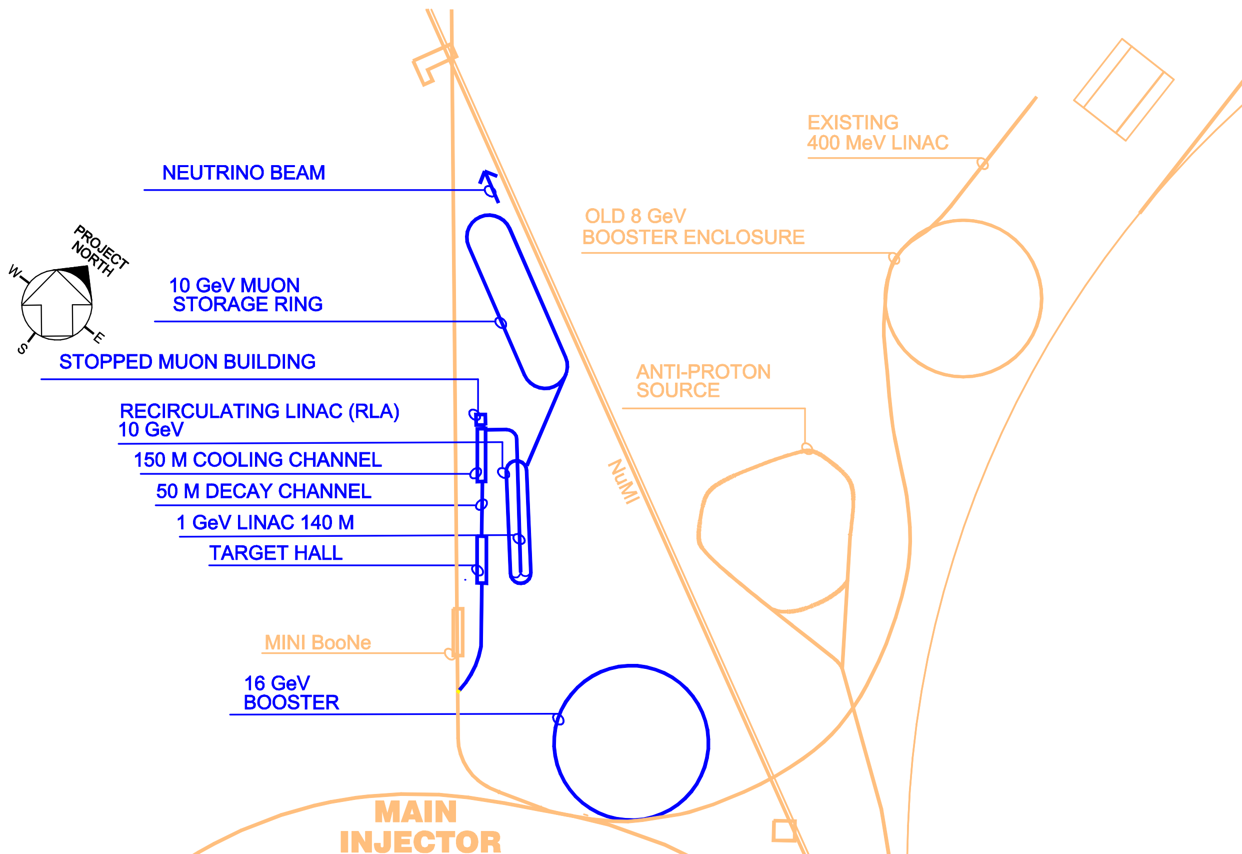

Figure 2: Schematic of the accelerator enclosures needed for Step 1. The target hall, decay channel, muon cooling channel, and acceleration systems are sited in a field near MiniBooNE. The stopped muon building is optional, depending on whether stopped muon physics is of sufficient interest to drive this addition to the program. See also photograph 1 at the end of this document.

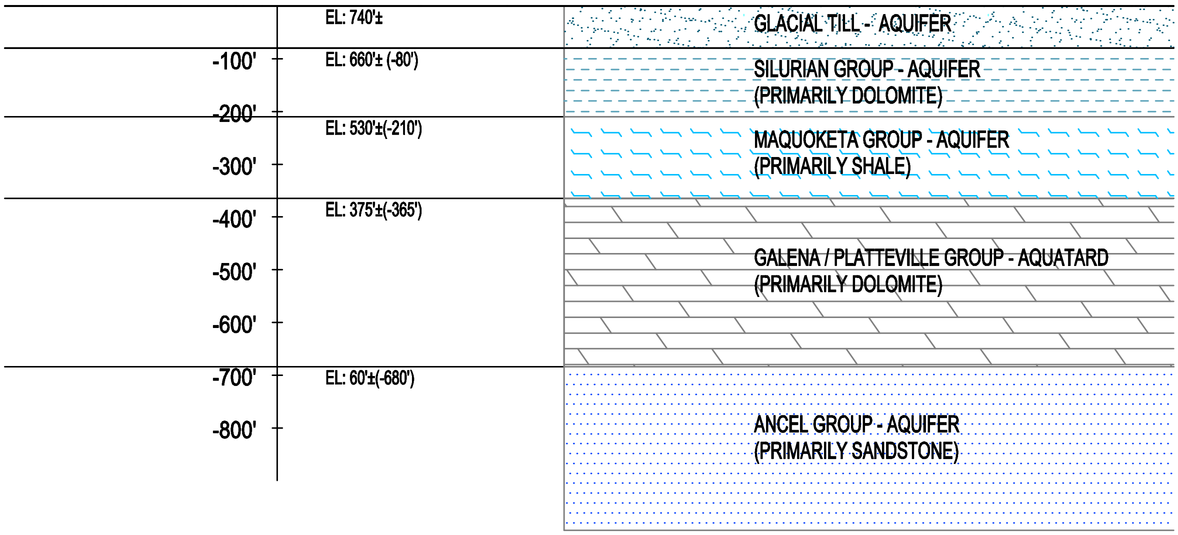

Figure 3: Schematic of the geological layers below the Fermilab site.

that in preliminary design studies this second acceleration stage has been taken to be a long linac. However, it seems likely that an RLA will be more cost effective. This requires further study. The extraction line from the RLA goes to a 10 GeV muon storage ring neutrino source, with a neutrino beam–forming straight section pointing at the Soudan Mine in Minnesota. Other interesting directions are summarized in Table 3.

The beam enclosures for the 10 GeV muon source can be constructed by cut and fill, although some parts might be housed in a building. Photograph 1 shows the target hall, decay channel, cooling channel, and acceleration systems fitting in a field south of Giese road, between the tree lines to the east and west, north of the Main Injector. This somewhat arbitrary choice was taken in order to avoid trees. The siting of the 10 GeV muon storage ring has not been carefully considered because it is not sufficiently constrained at this time. A ring producing a neutrino beam pointing at Soudan could be located near the surface based on cut and fill, or it could be located at a depth similar to NuMI. The elevation change from one arc to the opposite arc is significant for rings tilted at large angles, and this must be considered in deciding where to place a neutrino source pointing towards Europe or Japan, for example (see Table 3). The geology below Fermilab is well known (see Fig. 3). Our present understanding is that the vertical region below the surface that is “good” for blast and drill tunneling begins at a depth of about 150 ft, in the middle of the Silurian Group, and extends down to about 650 ft, close to the bottom of the $\sim$ 310 ft thick Galena/Platteville dolomite

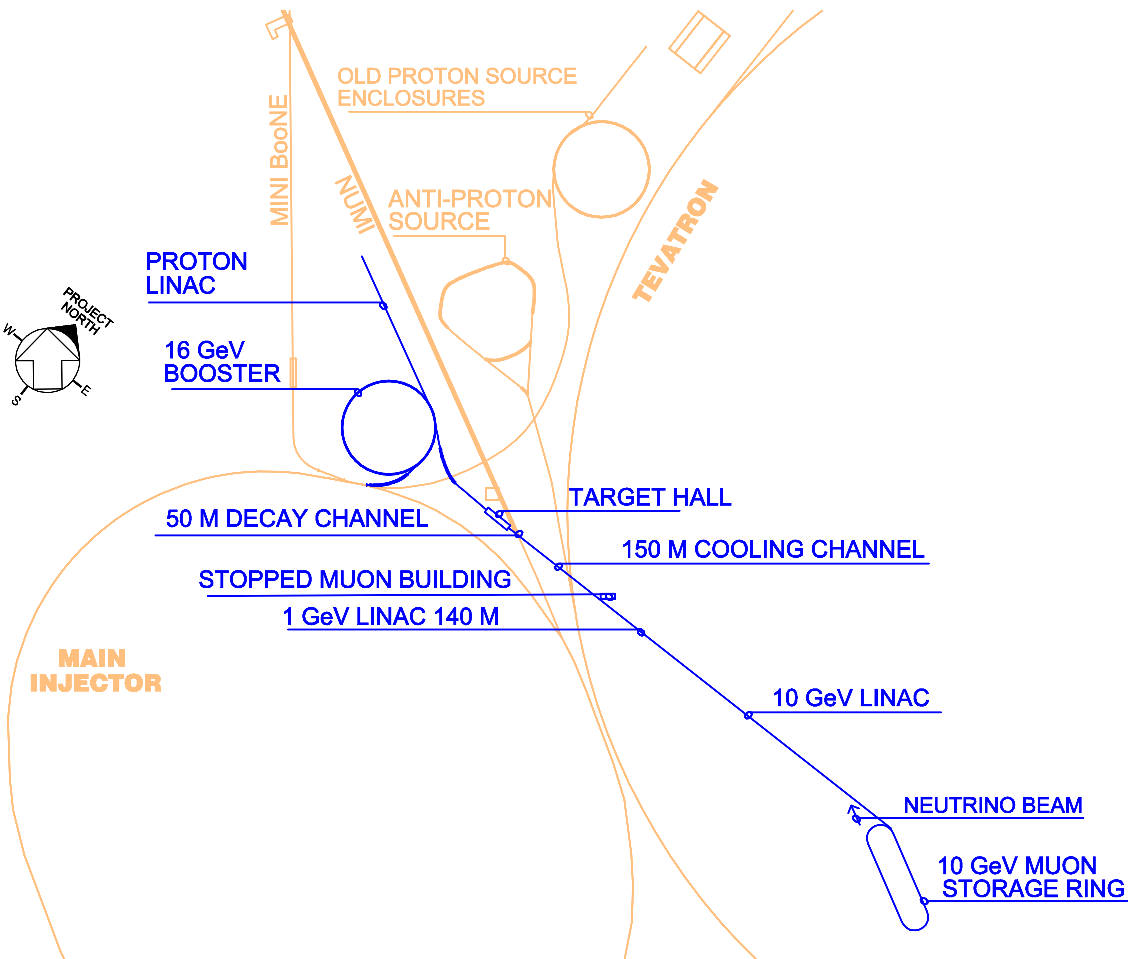

Figure 4: Schematic of an alternative location for the accelerator enclosures needed for Step 1, with the target hall, decay channel, cooling channel, and acceleration systems installed in a long straight tunnel. See also photograph 2 at the end of this document.

layer. Hence, the elevation change from the top to the bottom of a steeply tilted ring should not exceed about 500 ft. This "vertical acceptance" seems sufficient to accommodate a 10 GeV muon storage ring neutrino source pointing to Gran Sasso, or even the Kamioka mine.

One possible disadvantage of the configuration shown in Fig. 2 is that the Fermilab physics program would be interrupted whilst the new 16 GeV beam transport is installed in the MI8 enclosure. Figure 4 and photograph 2 show an alternative Step 1 configuration which uses a completely new set of enclosures for the new Proton Source, and also houses the muon cooling channel in a tunnel aligned with the decay channel and the 10 GeV acceleration systems. The muons are transported to a muon storage ring on the inside of the Tevatron ring. Note that the Linac and 16 GeV Booster are both in new beam enclosures. If the existing 400 MeV Linac was replaced with a new Linac one could consider continuing the ongoing physics program until the new Proton Source is functional. At that time, the 16 GeV beamline from the new Booster would be connected to the very downstream end of the MI8 enclosure and the physics program could then be continued with up to five times the hourly beam intensity. The particular location of the Proton Source shown in the figure is somewhat arbitrary, but this location minimizes the length of the extraction line to the downstream end of the MI8 enclosure. In principle, one could locate the new Proton Source further away from the Main Injector injection point and construct a longer extraction beamline without compromising performance.

2.3 Step 1: Physics Program

In our Step 1 vision, a greatly extended neutrino oscillation physics capability is the primary enhancement to the Fermilab physics program. It seems likely that in the next decade neutrino oscillations will remain a "hot physics topic". It is hoped that the next generation of approved neutrino experiments at Fermilab (MINOS and MiniBooNE) will establish the oscillation phenomenon, and perhaps begin to sort out the neutrino flavor mixing scheme, and measure the associated parameters. If this is the case, we can anticipate that a further generation of experiments at improved neutrino facilities will be required to better constrain the underlying neutrino masses, and to measure the mixing matrix that relates the neutrino flavor eigenstates to the mass eigenstates. Knowledge of these fundamental parameters may yield insights into physics at high energy scales (sea–saw mechanism ?) and into the origin of CP Violation (Is there CP violation in the neutrino system ?). Hence, in the following we focus on the impact of Step 1 on the neutrino physics program at Fermilab, and only briefly discuss the other physics possibilities.

Table 4: Summary of neutrino charged current event rates per kt-year at Soudan for three tunes of the NUMI beamline with 3.7×10^{20} POT per year, compared with various muon storage ring neutrino source options. The ν_τ rates assume $\nu_\mu \to \nu_\tau$ oscillations with $\sin^2 2\theta = 1$. Note that the fiducial mass of the MINOS detector is 5.4 kT, so in one year of data taking the MINOS experiment would see 5.4 times the number of events shown in the table.

Option	ν_μ	ν_e	$\overline{\nu_\mu}$	$\overline{\nu_e}$	ν_τ ($\Delta m^2 =$ 0.01 eV^2/c^4)	ν_τ ($\Delta m^2 =$ 0.001 eV^2/c^4)
Minos: Low Energy	458	5.4	64	1.3	27	0.5
Minos: Medium Energy	1439	13	45	0.9	135	2.6
Minos: High Energy	3207	18	34	0.9	312	4.1
μ–ring: 10 GeV μ^-	2217	–	–	958	259	4.6
μ–ring: 10 GeV μ^+	–	2035	1214	–	143	2.5
μ–ring: 15 GeV μ^-	7827	–	–	3377	893	12.1
μ–ring: 15 GeV μ^+	–	6631	3952	–	451	6.2
μ–ring: 20 GeV μ^-	18685	–	–	8016	1775	21.5
μ–ring: 20 GeV μ^+	–	15915	9526	–	906	11.0

2.3.1 MINOS Prime

The MINOS experiment is a long baseline search for muon–neutrino ν_μ disappearance as the neutrinos travel from Fermilab to the Soudan mine in Minnesota (L = 732 km). By 2002–3 the MI is expected to be delivering 4×10^{13} protons per pulse onto the MINOS target [11]. Downstream of the target two movable parabolic horns can be configured to maximize the beam flux at Soudan for different choices of average neutrino energy. The highest energy wide band beam (WBB) configuration yields a broad neutrino energy spectrum that peaks at ~16 GeV. The medium energy beam configuration yields a neutrino spectrum that peaks at ~7 GeV, and the low energy beam configuration yields a spectrum that peaks at ~3 GeV. The recent Super–Kamiokande results suggest that the lower neutrino energies may be desirable to probe the most favored region of the oscillation parameter space. The expected CC interaction rates at Soudan are shown in Table 4.

Within the framework of two–flavor oscillations, the $\nu_\mu \to \nu_x$ oscillation probability is given by the well known expression:

$$P(\nu_\mu \to \nu_x) \;=\; \sin^2(2\theta)\sin^2(1.27\Delta m^2 L/E)\;, \tag{1}$$

where θ is the mixing angle, and $\Delta m^2 \equiv m_3^2 - m_2^2$ is measured in eV$^2/c^4$, m_2 and m_3 are the masses of the two neutrino mass eigenstates, L is measured in km, and the neutrino energy E is measured in GeV. Super–Kamiokande's allowed region of parameter space is given approximately by $0.001 < \Delta m^2 < 0.01$ eV^2/c^4

for $\sin^2 2\theta = 1$. If Δm^2 is at the lower end of the allowed region (0.001 $\mathrm{eV}^2/\mathrm{c}^4$) then at Soudan $P = 0.09$ for 3 GeV neutrinos, and instead of the expected 4580 ν_μ CC interactions in a 10 kt–year exposure (two years of running with MINOS) there would be $\sim$ 4200 ν_μ CC interactions. Taking into account a 2% systematic uncertainty on the incident neutrino flux, the resulting disappearance signal would only be at the 2σ level. Hence MINOS can barely cover Super–Kamiokande's allowed region of parameter space. Higher statistics are clearly desirable.

The new 16 GeV Booster would, with some modest enhancements to the MI, allow a factor of 5 increase in the number of protons incident on the MINOS target. Provided the target station and decay tunnel are designed to shield against the increased associated radiation, this would enable a factor of 4–5 higher neutrino fluxes at Soudan. For example, in the absence of oscillations the low energy beam would yield $\sim$ 21000 ν_μ CC interactions in a 10 kt–year exposure. With neutrino oscillations and $\Delta m^2 = 0.001$ $\mathrm{eV}^2/\mathrm{c}^4$ there would be $\sim$ 19100 CC interactions, and taking into account a 2% systematic uncertainty on the incident neutrino flux, the resulting disappearance signal would be at the $\sim 4.5\sigma$ level. The proton source upgrade would therefore have an impact on the significance of the MINOS results if the oscillation parameters are in the unfavorable part of the allowed Super–Kamiokande parameter space.

Hopefully, oscillations occur with more favorable oscillation parameters, and an initial oscillation signal will be identified with a few years of MINOS running with the WBB. If this is the case, additional measurements with a narrow band beam would help pin down the oscillation parameters, and the relative contributions of the different oscillation modes. In the longer term the MINOS collaboration is exploring the possibility of supplementing the detector with an $\sim$ 1 kt hybrid emulsion detector to make a search for ν_τ interactions (a ν_τ appearance signal) and hence search for $\nu_\mu \to \nu_\tau$ oscillations. With the medium energy beam and a favorable value for Δm^2 of 0.01 $\mathrm{eV}^2/\mathrm{c}^4$, with $\sin^2 2\theta = 1$, there would be about 130 ν_τ CC interactions per kt–year at Soudan. If however nature has chosen the less favorable value $\Delta m^2 = 0.001$ $\mathrm{eV}^2/\mathrm{c}^4$, then this rate falls to ~ 4 ν_τ CC interactions per kt–year. These searches would benefit from higher neutrino fluxes. In fact the whole MINOS physics program would be significantly enhanced if it were possible to increase the fluxes at Soudan by a factor of a few or more. This would enable (i) a statistically marginal signal to become convincing, (ii) a convincing signal to become a more precise measurement of the oscillation parameters with the possibility of using a greater variety of beam conditions and energies within a finite time, and (iii) in the longer term, a statistically enhanced ν_τ appearance experiment with a hybrid emulsion detector.

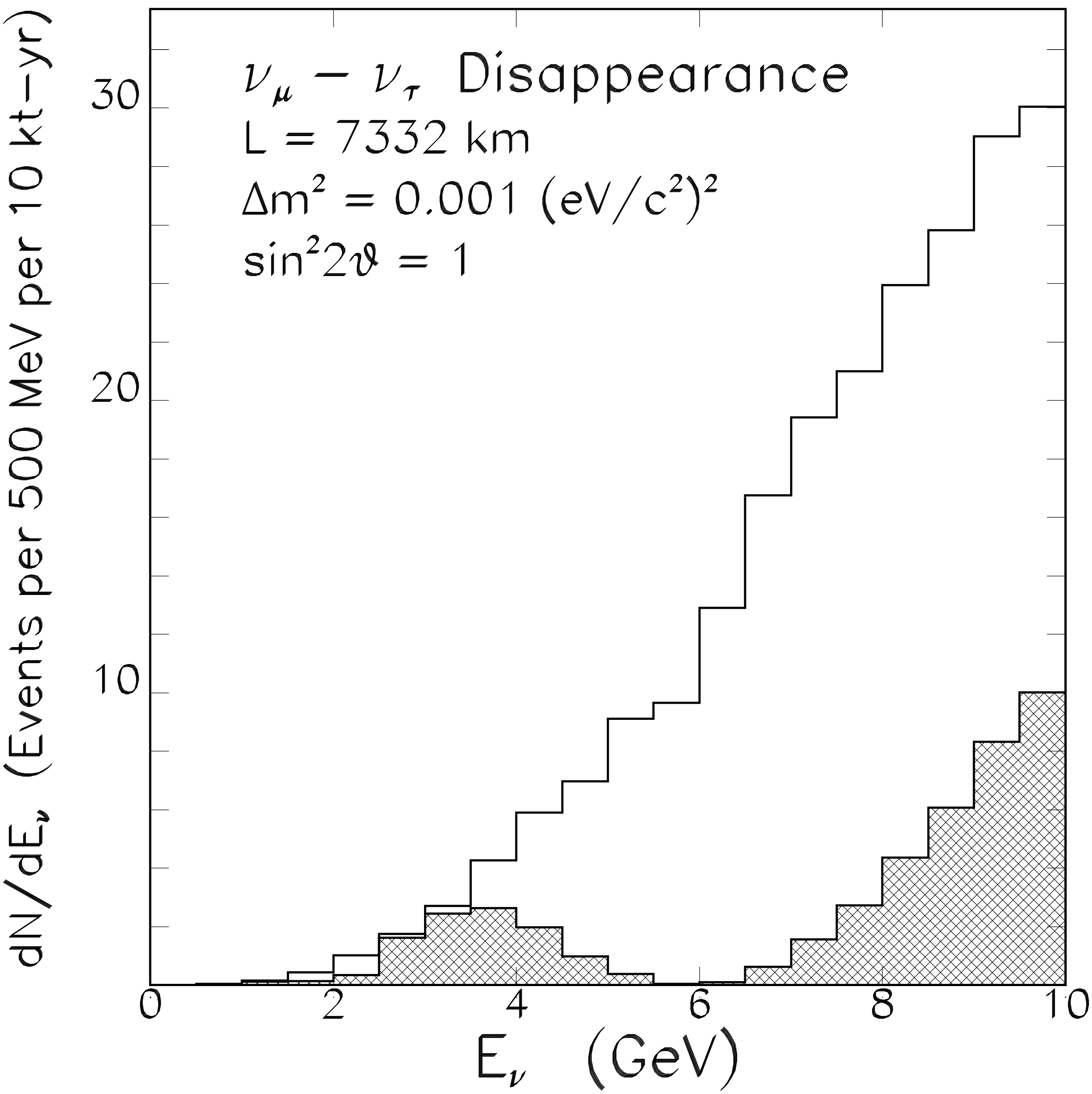

Figure 5: Predicted signal for $\nu_\mu \to \nu_\tau$ disappearance using a 10 GeV muon storage ring neutrino source at Fermilab pointed towards the Gran Sasso underground laboratory, assuming a 10 kt–year exposure. The open histogram is the prediction for the energy dependent CC interaction rate with no oscillations, and the shaded histogram is the prediction with oscillation parameters $\Delta m^2 = 0.001$ eV^2/c^4 and $\sin^2 2\theta = 1$.

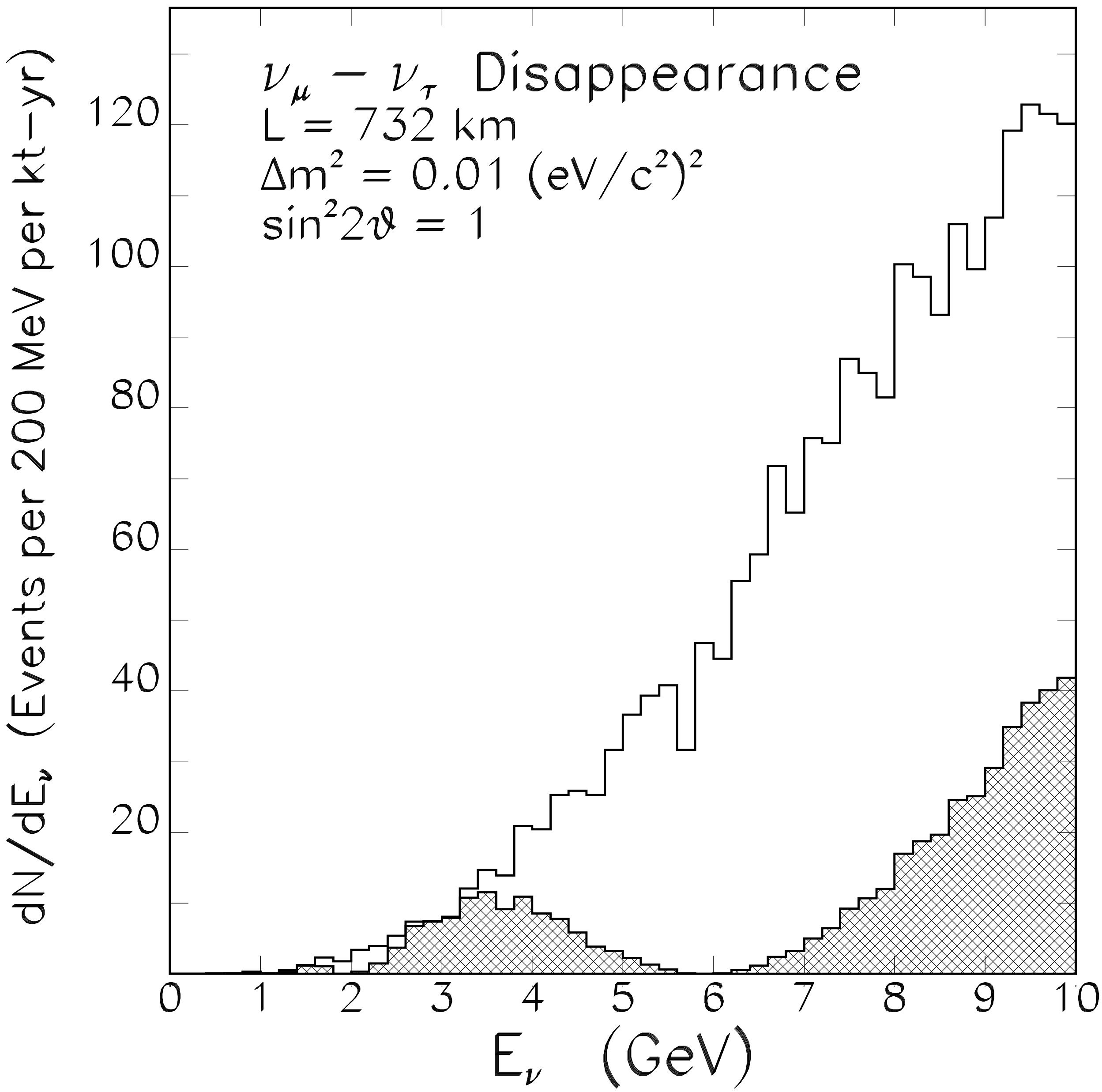

Figure 6: Predicted signal for $\nu_\mu \to \nu_\tau$ disappearance using a 10 GeV muon storage ring neutrino source at Fermilab pointed towards the Soudan mine in Minnesota. The open histogram is the prediction for the energy dependent CC interaction rate with no oscillations, and the shaded histogram is the prediction with oscillation parameters $\Delta m^2 = 0.01$ eV^2/c^4 and $\sin^2 2\theta = 1$.

2.3.2 Muon Storage Ring Neutrino Source

Muon storage ring neutrino sources offer the possibility of providing intense neutrino beams that (a) have precisely known fluxes, (b) are flavor pure (there is initially only one flavor of neutrino and one flavor of antineutrino in the beam), (c) have equal amounts of ν_μ and $\overline{\nu_e}$ (or ν_e and $\overline{\nu_\mu}$), and (d) if needed could be pointed downwards at large angles to send a neutrino beam through the Earth (Table 3). The optimum beam energy and baseline length for a future generation of neutrino oscillation experiments using a muon storage ring neutrino source will depend on, for example, the results from the MINOS experiment.

With the muon storage ring located at Fermilab, neutrino fluxes at the Soudan mine in Minnesota (L = 732 km), and at the Gran Sasso underground laboratory in Italy (L = 7332 km), have been computed [2, 12]. Downstream of the 10 GeV Step 1 muon storage ring, the annual neutrino and antineutrino fluxes at the distant sites are calculated to be 8×10^{11} m^{-2} and 8×10^{9} m^{-2} for respectively L = 732 km and 7332 km. If the finite muon beam divergence within the straight section of the storage ring is included in the calculation, the fluxes at the far sites are decreased by ~10%. With these fluxes, in the absence of neutrino oscillations, there will be $\sim 2.2 \times 10^4$ ($\sim 2.2 \times 10^2$) charged current ν_μ interactions per operational year in a 10 kt detector at L = 732 km (L = 7332 km).

To illustrate the physics potential of a 10 GeV muon storage ring neutrino source with a baseline length of 7332 km (Fermilab $\rightarrow$ Gran Sasso), consider a search for $\nu_\mu \rightarrow \nu_\tau$ oscillations, and assume that Δm^2 is at the lower end of the range suggested by the Super–Kamoikande results ($\Delta m^2 \sim 0.001$ eV^2/c^4 with $\sin^2 2\theta = 1$). With the muon storage ring neutrino beam described above, the predicted ν_μ disappearance signal at Gran Sasso is shown in Fig. 5. The oscillation signal is striking. With no oscillations, 221 ν_μ CC interactions per 10 kt–yr would be expected. With oscillations this number is reduced to 45 ν_μ CC interactions per 10 kt–yr, with a very different energy spectrum.

To illustrate the physics potential of a 10 GeV muon storage ring neutrino source with a baseline length of 732 km (Fermilab $\rightarrow$ Soudan), consider a search for $\nu_\mu \rightarrow \nu_\tau$ oscillations, and assume that Δm^2 is towards the upper end of the range suggested by the Super–Kamoikande results ($\Delta m^2 \sim 0.01$ eV^2/c^4 with $\sin^2 2\theta = 1$). In this case the MINOS experiment should establish a convincing disappearance signal. With the muon storage ring neutrino beam described above, the predicted ν_μ disappearance signal at Soudan is shown in Fig. 6. The oscillation signal is striking. With no oscillations, 22170 ν_μ CC interactions per 10 kt–yr would be expected. With oscillations this number is reduced to 4470 ν_μ CC interactions per 10 kt–yr, with a very different energy spectrum. In addition, in a 1 kt hybrid emulsion detector, 259 ν_τ CC interactions would be expected per operational year. Note that if the charge of the τ lepton was also measured, then $\nu_\mu \rightarrow \nu_\tau$ oscillations can be distinguished from $\nu_e \rightarrow \nu_\tau$ oscillations, and the sensitivity for $\nu_e \rightarrow \nu_\tau$ oscillations would be comparable to the sensitivity for $\nu_\mu \to \nu_\tau$ oscillations ... a unique physics capability of the muon storage ring neutrino source. Finally, other Fermilab $\to$ Soudan muon storage ring scenarios are summarized in Table 4.

2.3.3 Other Physics Possibilities: Low energy Kaon and Muon physics

The proton source required for the FMC would allow a continuation of low and intermediate energy kaon physics with intensities a factor of 20 more than presently available at the AGS, and a factor of a few greater than foreseen at the Fermilab MI, an upgraded AGS, or the proposed KEK JHF. Rare kaon decays and precision kaon CP and CPT studies can provide windows on physics beyond the Standard Model and are likely to remain of interest well into the future. As an example consider the rare decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$. Precise measurements of these decay modes would enable a precise determination of V_{td} and the CP violation parameter η. The first $K^+ \to \pi^+\nu\bar{\nu}$ event has been reported by the BNL E787 collaboration. The decay $K_L \to \pi^0\nu\bar{\nu}$ has not yet been observed. Future experiments at the AGS and at the Fermilab MI may yield a few of these rare K^+ and K_L decays per year. It has been estimated [13] that at the muon collider proton source of order 100 events per year could be observed in each mode. However, this kaon physics program would require the addition of a stretcher ring to the FMC proton source. Other interesting kaon experiments that might be pursued include muon transverse polarization in $K^+ \to \pi^0\mu^+\nu_\mu$ or $K^+ \to \mu^+\nu_\mu\gamma$, spin–spin correlations in $K^+ \to \pi^+\mu^+\mu^-$, and polarization effects in $K_L \to \mu^+\mu^-$.

The Step 1 muon source would provide low energy muon beams with intensities of 10^{14} μ per second. This is an enormous increase over the fluxes available at current low energy muon beam facilities, which produce typically 10^7–10^8 μ per second. Hence, a small fraction of the muons at the Step 1 facility could be used to support a broad range of low energy muon experiments. Examples are searches for muon–number violation in rare muon decays ($\mu \to e\gamma$, $\mu \to eee$), muonium–antimuonium oscillation, or $\mu \to e$ conversion. However, it should be noted that in general the bunch structure at the muon source is not ideal for low energy muon experiments that tend to require either a DC muon beam to minimize instantaneous rates, or a CW beam with $\sim 2\mu$s between bunches. Further study is needed to assess the real potential for exploiting the extremely high muon intensities at a low energy Step 1 muon facility.

2.4 Step 1: Schedule Considerations

We can only speculate on what might be a plausible schedule for the Step 1 facility upgrade. Nevertheless, attempting to imagine what a reasonable, but aggressive, schedule might be helps to focus on the critical path. A vigorous R&D program will be needed before the Step 1 muon source, acceleration system, and storage

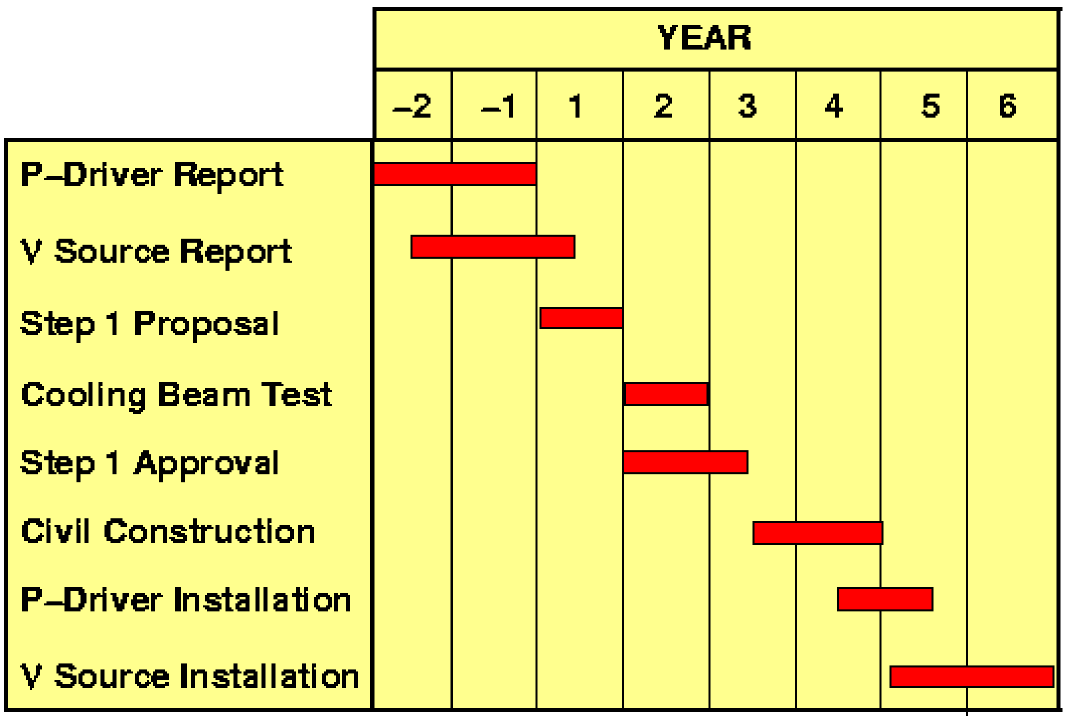

Figure 7: Speculative schedule for the Step 1 upgrade, with "Year 1" defined as the year in which the Step 1 proposal is finalized and submitted.

ring could be built. We will assume this is undertaken, and goes well.

Our speculative schedule is summarized in Fig. 7. A proton driver upgrade design study is currently in progress, with the goal of delivering a design report by the end of 2000. If a similar activity was initiated for a muon storage ring neutrino source, it is plausible that a Step 1 design report could also be available by mid–2001. We can only guess at the time required for approval and construction ... we will guess that 5 years is aggressive but not impossible, with the proton driver upgrade part of the project completed in 3–4 years. Defining "Year 1" as the year in which the Step 1 proposal is finalized and submitted, the ability to accelerate a factor of 5 more protons in the MI would come in "Year 5", and the muon storage ring neutrino source would begin operation in "Year 7".

3 Step 2: The First Muon Collider

In the following we will assume that the FMC will have a center–of–mass energy between 100 GeV and 500 GeV. To be explicit, we will consider two possible FMC choices, namely:

(a) An s–channel Higgs factory with $m_H = 110$ GeV/c^2, and hence the muon collider beam energies are $E_\mu = 55$ GeV. This scenario makes sense if a Higgs–like boson is discovered before or during early LHC running, and no other new particles have been discovered.

(b) A 500 GeV muon collider ($E_\mu = 250$ GeV). This would be a sensible choice if new particles had been observed within this energy range at, for example, the LHC.

3.1 Step 2: Facility Upgrade

A muon collider accelerator complex is shown schematically in Fig. 8. The decay channel and parts of the required proton driver, pion production target system, and muon cooling system would be in place from the Step 1 upgrade. Further upgrades to the proton and muon sources would be needed in Step 2, along with the addition of a muon acceleration system, collider ring, and experiment. The Step 2 facility upgrade is summarized in the following.

3.1.1 The Proton Source Upgrade

The Step 2 proton source upgrade corresponds to the phase 2 upgrade shown in Table 1, and consists of upgrading the 400 MeV Linac energy to 1 GeV and adding a 3 GeV Pre–booster. The upgraded proton source accelerates protons to 16 GeV, is cycling at 15 Hz, and produces 4 proton bunches per cycle, each containing 2.5×10^{13} particles. These parameters are based on the Fermilab summer study summarized in Ref. [4], updated with recent ideas [5].

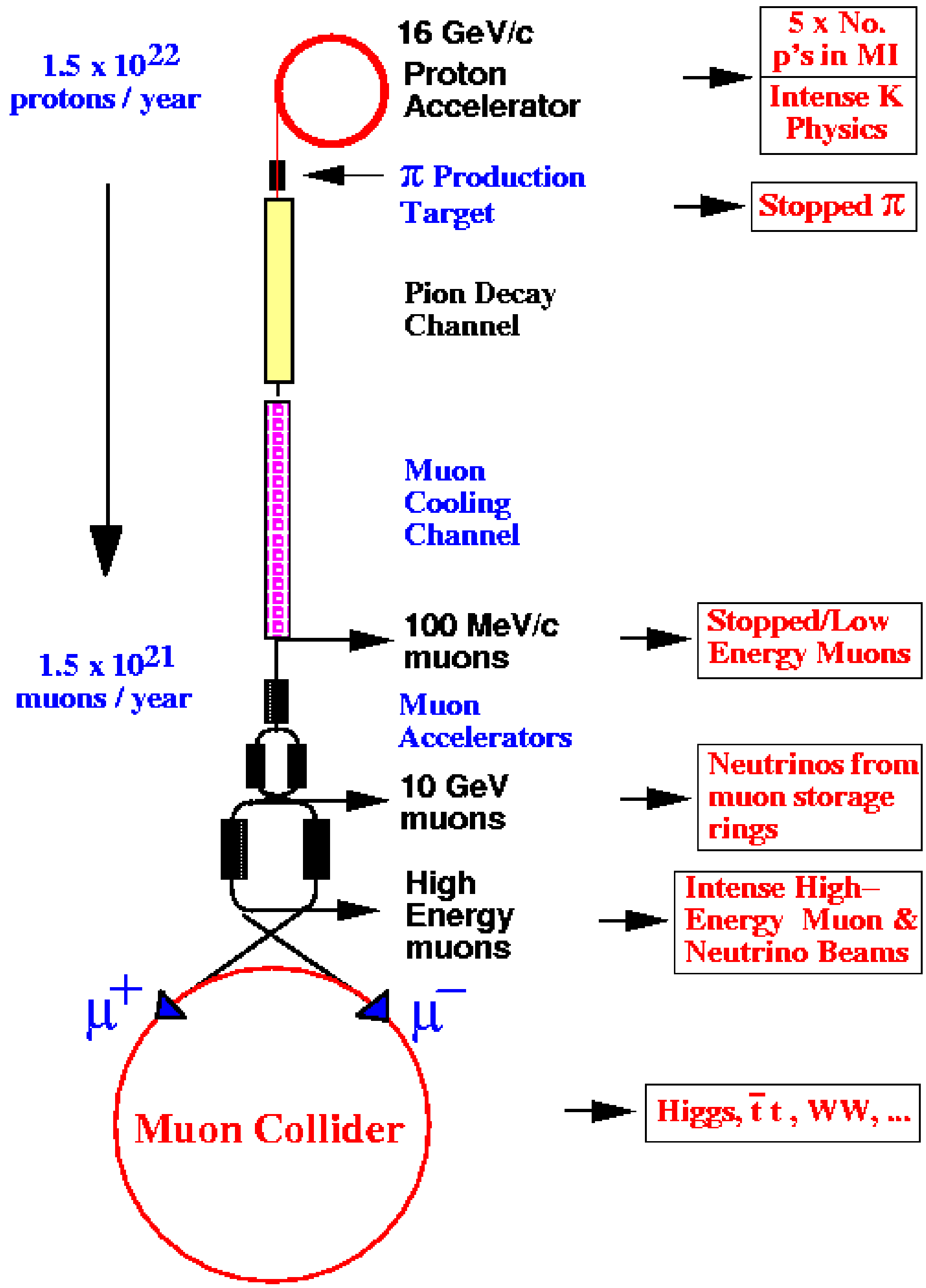

Figure 8: Schematic showing the components of a muon collider accelerator complex.

Table 5: Parameters of muon bunches downstream of the FMC ionization cooling channel.

	Narrow σ_p	Broad σ_p
muons per bunch	8.5×10^{12}	8.5×10^{12}
μ^+ bunches per cycle	1	1
μ^- bunches per cycle	1	1
Momentum (MeV/c)	200	200
σ_p/p	5%	10%
Bunch length (cm)	1.8	10
Normalized $\epsilon_\perp$ (mm–mr)	200π	60π
Repetition rate (Hz)	15	15
μ^- per year (10^7 secs)	1.3×10^{21}	1.3×10^{21}

3.1.2 The Muon Source Upgrade

The Step 2 muon source upgrade consists of upgrading the pion production target to survive the 4 MW proton beam power of the phase 2 proton source, and upgrading the cooling channel with an additional long section to further reduce the 6–dimensional beam emittance for a high luminosity muon collider. The length of this additional cooling section is estimated to be in the range of 400–800 m.

The upgraded muon source will produce muon bunches using two proton bunches extracted from the proton source, and combined to form a super–bunch containing 5×10^{13} protons incident on the pion production target. The first super–bunch would be used to make and collect positive muons, and the second used for negative muons. Each super–bunch interacts to produce $\sim 3 \times 10^{13}$ charged pions of each sign captured within the high field solenoid decay channel. At the end of the decay channel described in Section 2.1.2 there would be 1.7×10^{13} muons per bunch. In an operational year $\sim 5 \times 10^{21}$ muons would exit the decay channel, 2.5×10^{21} in positive muon bunches and 2.5×10^{21} in negative muon bunches. A high luminosity muon collider will require the 6–dimensional phase–space occupied by the muons within the muon bunches exiting the decay channel to be reduced by a factor of 10^5–10^6. This will require a cooling channel that in the current muon collider feasibility study design is about 600 m long. At the end of the cooling channel each muon bunch is expected to contain about 8.5×10^{12} muons with a momentum of order 200 MeV/c, a momentum spread given by $\sigma_p/\mathrm{p} \sim 0.05$, a bunch length $\sigma_Z \sim 1.8$ cm, and a transverse emittance $\epsilon_N \sim 200\pi$ mm-mrad. In an operational year (10^7 secs) there are 1.3×10^{21} muons of each sign exiting the decay channel.

Table 5 summarizes the properties of the muons at the end of the cooling channel. Note that the phase–space occupied by the muons can be optimized

Table 6: Muon accelerator parameters for a 2×2 TeV Collider. The acceleration scheme is based on Ref. [5], but modified to produce 2 TeV beams.

	Linac	RLA1	RLA2	RLA3	S1	S2	S3
Input Energy (GeV)	0.1	0.7	2	7	70	250	1250
Output Energy (GeV)	0.7	2	7	70	250	1250	2000
Circumference (km)	0.07	0.12	0.26	2.27	5.81	15	15
No. of Turns	2	8	10	12	18	27	20
Loss (%)	6.1	12.3	10.8	14.6	11.2	9.9	3.0
rf Freq (MHz)	200	100	200	200	800	1300	1300
Acc. Gradient (MV/m)	8	8	10	10	15	25	25
Acc./turn (GeV)	0.40	0.17	0.50	5.25	10	37.5	37.5
Acc. time (μs)		3	8	91	349	1351	1001

either to maximize the luminosity of the collider, or alternatively to minimize the beam energy spread at the expense of luminosity.

3.1.3 Acceleration and the First Muon Collider Ring

The muons exiting the cooling channel must be rapidly accelerated to high energy before they decay. A number of different acceleration schemes have been considered. The one summarized in Table 6 is based on Ref. [5]. In this scheme the FMC acceleration system would consist of a linac to accelerate the muons to 700 MeV, followed by 3 recirculating linear accelerators (RLAs), to produce muons with energies of up to 70 GeV. For our Higgs factory example the FMC would take beams from RLA3 at 55 GeV. Note that in this case 63% of the muons survive the acceleration system. Hence, there are 5.4×10^{12} muons per bunch available for the Higgs factory. For our 500 GeV muon collider example, 70 GeV beams from RLA3 would be injected into a synchrotron (S1) and accelerated to 250 GeV. In this case 49% of the muons survive, and there are 4.2×10^{12} muons per bunch available for the FMC.

For both the Higgs factory and 500 GeV examples, the high energy muons are injected into the muon collider, which is a storage ring using high–field dipoles to minimize the orbit length and hence maximize the number of revolutions before muon decay has reduced the luminosity to an uninteresting level. The ring is therefore relatively compact. For example, a 110 GeV collider ring would be comparable in size to the existing Antiproton Accumulator ring. A 500 GeV collider ring would be about one–sixth of the size of the existing Tevatron. The FMC average luminosity for a 110 GeV collider would be $L \sim 4 \times 10^{31}$ cm^{-2} s^{-1} with a beam energy spread of 0.01%, or alternatively $L \sim 2 \times 10^{31}$ cm^{-2} s^{-1} with a beam energy spread of 0.003%. The average luminosity for a 500 GeV collider would be $L \sim 1 \times 10^{33}$ cm^{-2} s^{-1} with a beam energy spread of 0.14%.

3.2 Step 2: Siting Issues

Figure 9 and photograph 3 show the muon source, RLA1, and RLA2 sited close to the 16 GeV Booster. The upgrade of the proton linac energy to 1 GeV requires an extension of the linac which is assumed to be possible within the present beam enclosures. The 3 GeV Pre-booster is located close to the 1 GeV linac and is in a new enclosure. The 7 GeV muon beam from RLA2 is transported to the inside of the Tevatron ring where it is injected into RLA3, and either (i) accelerated to 55 GeV and injected into a Higgs factory, or (ii) accelerated to 70 GeV, injected into S1, further accelerated to 250 GeV, and finally injected into a 500 GeV collider ring.

We have considered the possible locations for the FMC detector. The only constraint for the Higgs factory detector that we are aware of at this time is that it should be at the same depth as RLA3. A convenient position in the FMC ring may be opposite to the RLA3 extraction point. There are, however, several criteria for the location of the 500 GeV FMC detector. It is thought that it might be useful to locate it near the existing infrastructure for one of the large detectors at Fermilab. We chose CDF because of the location of the energy frontier detector described in Section 4. In addition, the FMC will need cryogenics and the Central Helium Liquefier is located near CDF. Note that we have also included a beam line to a muon storage ring tangent to the Tevatron at D0 for a possible μp collider experiment.

The Galena-Platteville layer of rock under the Fermilab site is composed of material which is very good for tunneling. It extends from approximately 360 feet to 690 feet under the site (Fig. 3). It is an aquatard, but is located above an aquifer that we wish to avoid. The VLHC group at Fermilab has developed a tunneling cost estimate [14] for a 3 TeV injector which is slightly larger than the size of the Fermilab site and is located in the Galena-Platteville layer. If we assume the sizes of the muon collider accelerator enclosures are approximately the same as this VLHC injector, we can use their estimate of $1240 per foot for making an approximate cost estimate for tunnels in this rock layer. This can be compared to the cost of cut and fill for a shallow FMC, which at this time is thought to be larger.

In our vision, we have located the FMC in the top of the Galena-Platteville dolomite rock layer 480 feet under the surface. This choice requires the 7 GeV beam transport line to have a slope of about 8% in order to arrive deep enough in the top of the Galena-Platteville layer to construct beam and detector enclosures. The FMC ring and detector would be built and operated at depths comparable to the depths of the big detectors at the CERN LEP collider.

An alternative is to locate the FMC near the surface. However, a shallow FMC

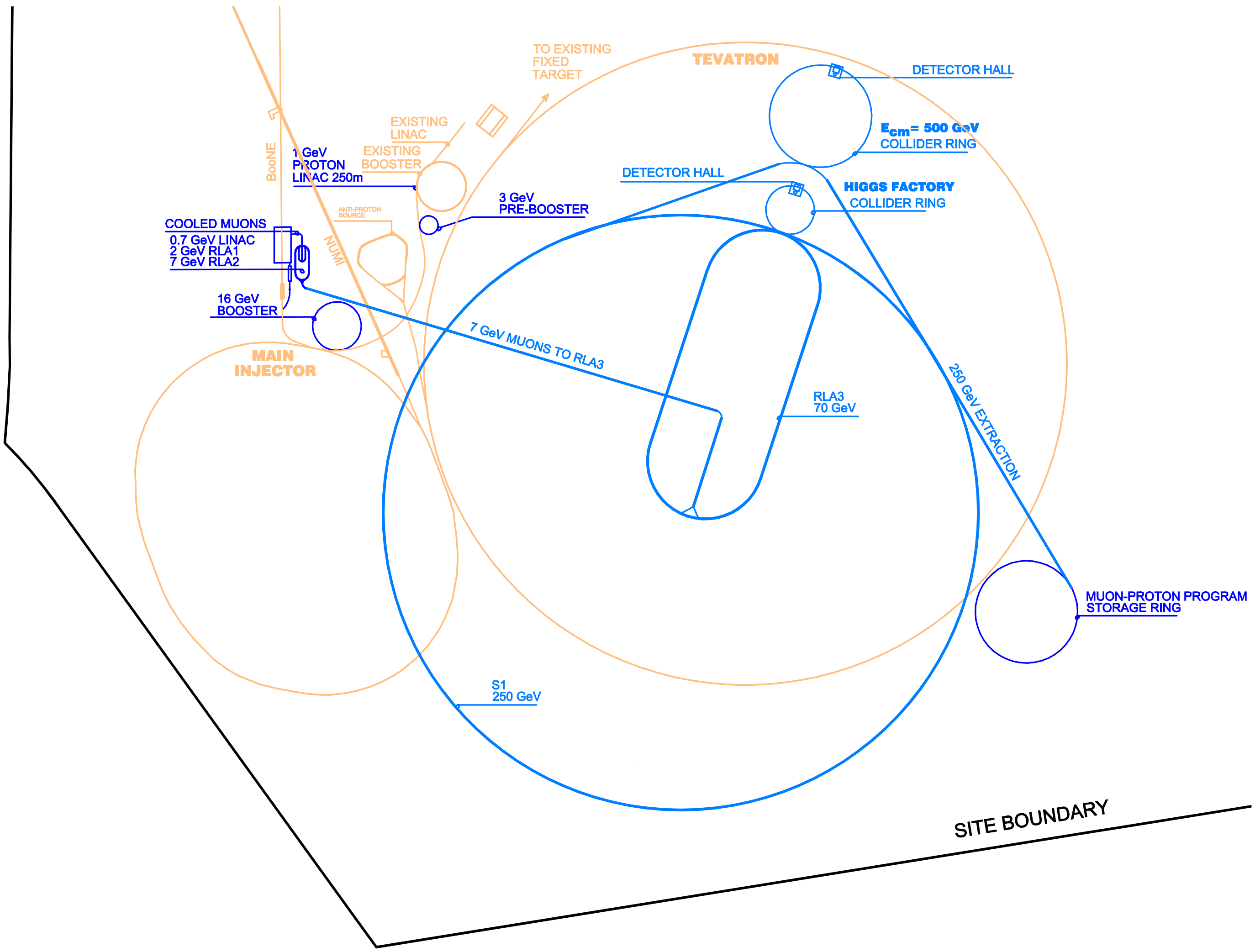

Figure 9: Schematic of the accelerator enclosures needed for Step 2. See also photograph 3 at the end of this document. RLA3 and the collider rings are located in the Dolomite layer below Fermilab. The μp collider is optional.

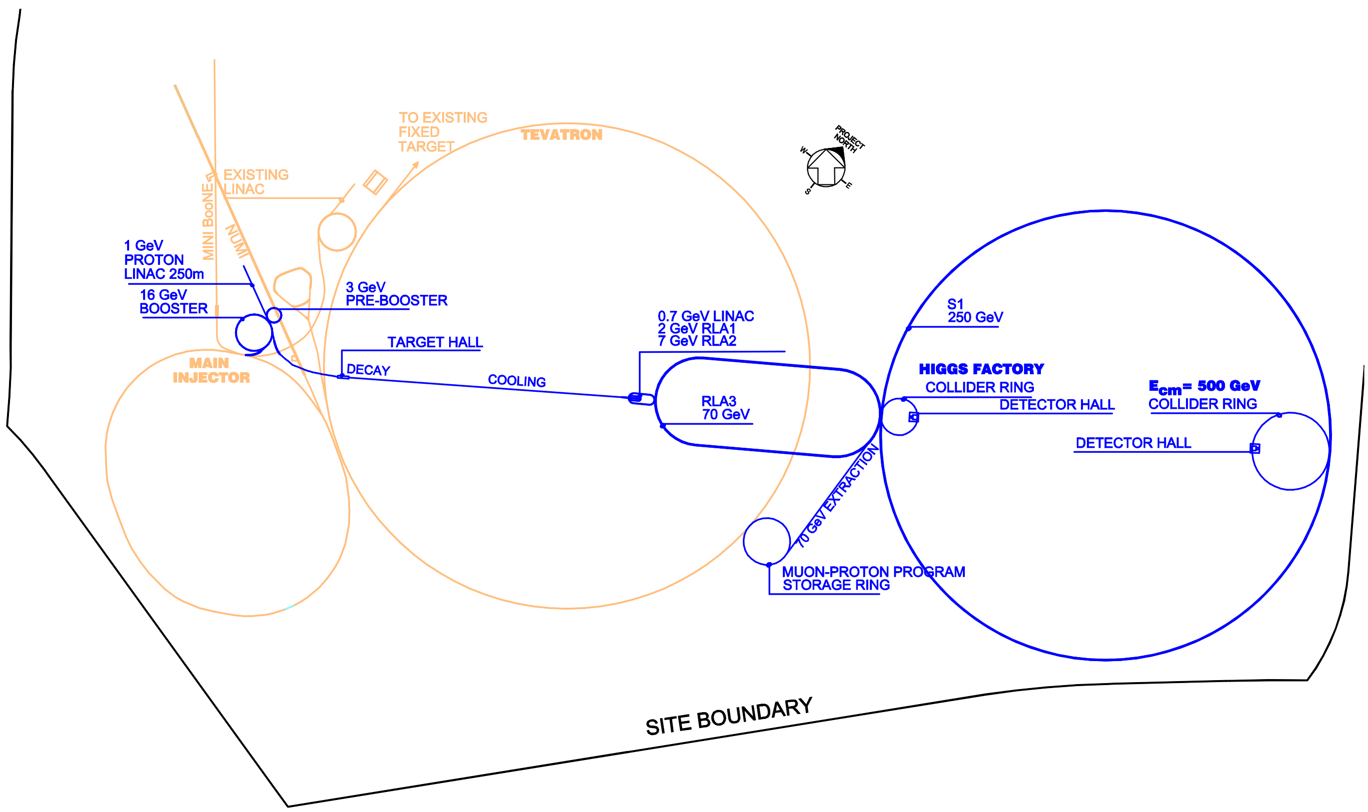

Figure 10: Schematic of an alternative scheme for the accelerator enclosures needed for Step 2. See also photograph 4 at the end of this document. All beam enclosures are near the surface. The μp collider is optional.

would probably disturb the environment more than a deep FMC. A near–surface layout for the FMC accelerator complex is shown in Fig. 10 and photograph 4. In this layout the primary protons are transported to a target hall on the inside of the Tevatron ring, and the pion decay channel and muon cooling channel are located in a long straight tunnel. The 500 GeV FMC ring and its injector occupy the South–Eastern corner of the Fermilab site.

3.3 Step 2: Physics Program

If a light Higgs boson is discovered in the next few years, then a good choice for the FMC might be a Higgs factory. If no Higgs–like boson is discovered before construction of the FMC begins, or if other more exciting new particles are discovered within reach of a 500 GeV FMC, then a 500 GeV collider might be the right choice. The physics potential for these two options is summarized in Ref. [5].

The Step 2 physics facilities would include :

(i) The FMC, either a Higgs factory or a 500 GeV collider.

(ii) Neutrino beams from one or more muon storage ring neutrino sources, and/or neutrino beams that necessarily are formed downstream of the straight sections in the RLAs.

The Step 2 physics facilities might also include :

(iii) An intense low energy kaon physics facility using the 16 GeV Booster.

(iv) Conventional low energy neutrino beams using the 16 GeV Booster.

(v) An intense stopped pion physics facility.

(vi) An intense low energy muon physics facility.

(vii) A 70 GeV (or 250 GeV) $\times$ 1000 GeV μ p collider (this needs further study).

3.3.1 Physics at a Higgs Factory

The production of Higgs–like bosons in the s–channel with interesting rates is a unique capability of a muon collider. The goals of an FMC Higgs factory would be to measure the Higgs mass, width, and branching fractions with sufficient precision to differentiate between a standard model Higgs boson, and the light Higgs–like boson of the minimal supersymmetric extension to the Standard Model (MSSM). In addition, within the MSSM there are heavier neutral Higgs bosons (H^0 and A^0) which the FMC measurements might be able to locate in preparation for higher energy muon collider upgrade options.

It has been shown [5] that the length of time needed for scanning the Higgs resonance and making the required measurements is of order 1 year to complete the first scan of a 110 GeV/c^2 Higgs boson and measure its mass with a precision of $\Delta m_h \sim 1$ MeV/c^2. With a further 2 years of running at 0.2 fb^{-1} per year, the following precisions could be achieved: 16% for Γ_{Tot}, 1% for σ·B($b\bar{b}$), and 5% for σ·B($WW^\star$). The ratio B($b\bar{b}$)/B($WW^\star$) would be sensitive to the presence of a heavier A^0 boson up to masses of about 500 GeV/c^2. Thus, the FMC would be a world class machine offering a cutting–edge physics program at Fermilab.

3.3.2 Physics at a 500 GeV FMC

If there are new particles (MSSM particles, techni–particles , ...) with masses within reach of a 500 GeV lepton–antilepton collider then they will probably be discovered at the LHC. We take the particles of the MSSM as a popular example. Although the LHC may be a great discovery machine, it will be very difficult, perhaps impossible, at the LHC to (i) make a precise measurement of the mass of the lightest suspersymmetric particle (LHC measurements give sparticle mass differences), (ii) study sleptons with masses greater than about 200 GeV/c^2, (iii) study heavy gauginos which are mainly Higgsino, and (iv) study heavy Higgs bosons if $\tan\beta$ is not large. We can anticipate that a 500 GeV FMC would have an extensive physics program to pursue.

3.3.3 Physics at the Front–End

We note in passing that with the further Step 2 upgrades of the proton source and muon source, and with the addition of high energy intense muon beams, the potential non–muon–collider physics program at Fermilab would be enhanced, with several options for extending, for example, the neutrino physics program.

3.4 Step 2: Schedule Considerations

Once again, we can only speculate about what might be an aggressive, but plausible, schedule. Our guess is shown in Fig. 11. We assume that the current muon collider feasibility studies go well, and that by "Year 6" (with "Year 1" defined as the Step 1 proposal year) a Step 2 conceptual design report could be completed, with the Step 2 proposal submitted at the end of "Year 6". This would coincide with the completion of the Step 1 upgrade. Allowing 18 months for the approval process, there will be significant experience with the Step 1 muon source before the Step 2 construction begins. In our speculative schedule the FMC would be completed in "Year 11", after 4-5 years of dedicated Step 1 muon storage ring neutrino source running.

4 Step 3: Recapturing the Energy Frontier

Our ultimate muon collider goal is to build a high energy muon collider with a center–of–mass energy of 4 TeV, and recapture the energy frontier at Fermilab.

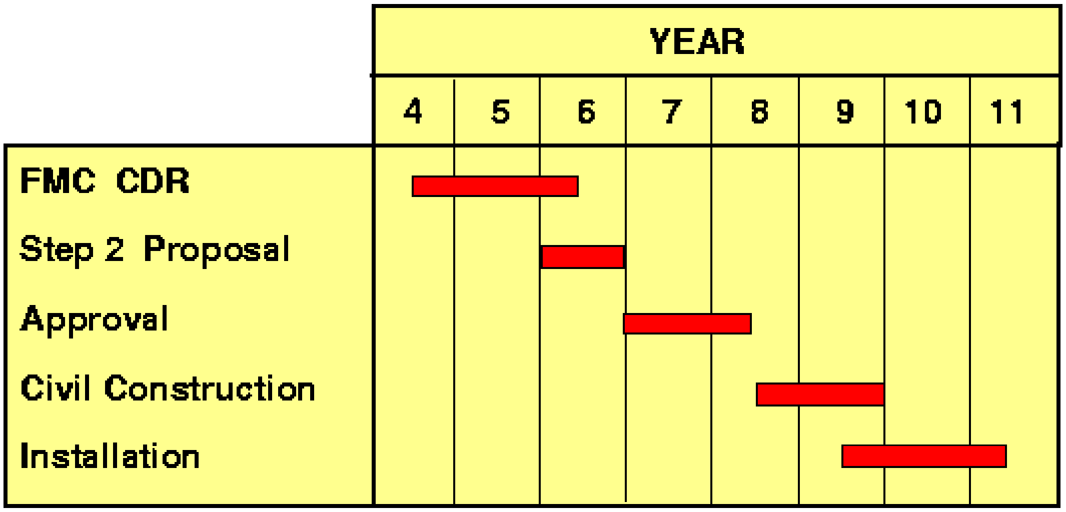

Figure 11: Speculative aggressive schedule for the Step 2 upgrade. “Year 1” is defined as the year in which the Step 1 proposal is finalized and submitted.

4.1 Step 3: Facility Upgrade

The Step 3 facility upgrade would consist of building further site–filling muon acceleration systems to raise the muon beam energy to 2 TeV (see Table 6), constructing a 4 TeV collider ring which would be about the size of the present Tevatron ring, and building a high energy muon collider detector facility.

4.2 Step 3: Siting Issues

Figure 12 and photograph 5 show the elements needed for the Step 3 upgrade. The sizes of the accelerator enclosures are based on Table 7.6 of Ref. [15], modified to accommodate a 4 TeV collider (rather than 3 TeV). We would locate the energy frontier collider ring and its accelerators as close as possible to the bottom of the Galena-Platteville dolomite rock layer. This puts them at about 600 feet below the surface of the Fermilab site. Instead of sending beam to the FMC collider ring, beam transfer lines send it to S2 (synchrotron 2) and S3, which are located in a common beam enclosure. The circumference of this tunnel is sized to fit under the Fermilab site. After joining S3 to the injection lines of the high energy muon collider ring, and locating the detector opposite to this injection point, the detector is located under the neighborhood of CDF. Also note that the abort lines from the collider fit under the Fermilab site and are in solid rock. The residual radiation is therefore contained under the Fermilab site.

The energy frontier collider ring has a unique radiation issue. It is placed as deep as possible under the Fermilab site because of the radiation resulting from

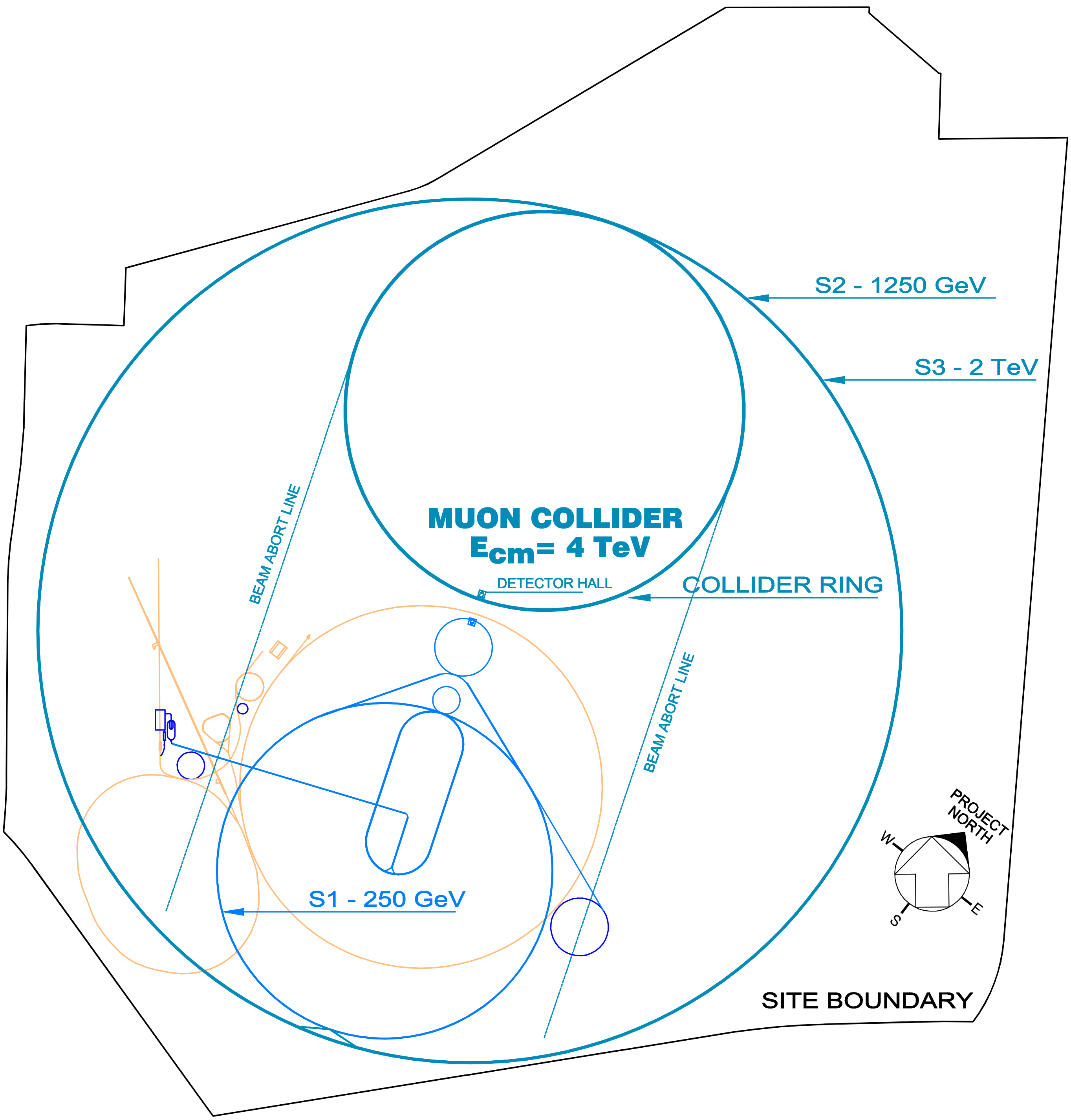

Figure 12: Schematic of the accelerator enclosures needed for Step 3. See also photograph 5 at the end of this document. The high energy accelerator complex and collider are constructed in tunnels within the Dolomite layer below Fermilab.

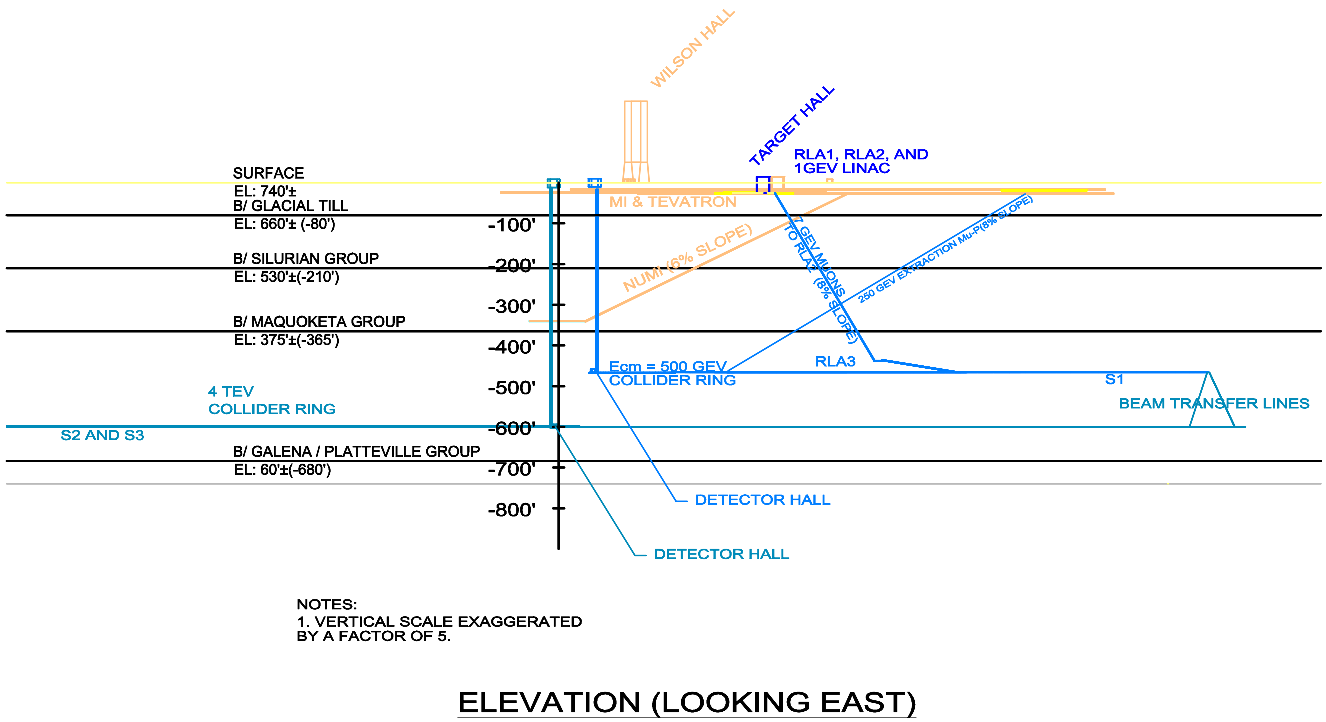

Figure 13: The elevations of the accelerators are shown from a perspective looking east. The horizontal scale is compressed by a factor of five with respect to the vertical scale. Wilson Hall is shown for reference.

the interaction of neutrinos with the earth. The neutrinos are produced from the decay of the muons around the circumference of the collider ring. If the muon beams are held steady in the collider, the neutrinos are tightly collimated in a disc which starts in the rock at the level of the collider ring, extends underground in all directions off-site, until it finally exits the surface of the Earth at some radius from the collider. The center of mass energy and the depth of the collider can be chosen so that the radiation level at the exit of the surface of the Earth is equal to the Fermilab limit for the annual dose to the public [16]. For example, a collider located at a depth of 600 ft has a neutrino exit radius of 30 miles. Figure 13 shows the accelerator beam enclosures as they would be located under the Fermilab site.

4.3 Step 3: Physics Program

In the final step a 4 TeV collider is constructed to recapture the energy frontier at Fermilab. The Step 3 muon collider might be designed to scan any massive resonant phenomenon discovered previously at the LHC, for example, or indicated by precision measurements at the FMC. If no high–energy resonances have been discovered before the high energy muon collider proposal, then it is likely that measurements of the scattering of longitudinally polarized W bosons at the highest possible energies will be very important. The high energy muon collider would provide a frontier tool for probing the strong scattering of weak bosons. In addition, the front–end physics potential would be further enhanced with, for example, the possibility of very high–energy neutrino experiments using compact highly instrumented detectors.

4.4 Step 3: Schedule Considerations

We can only offer some general considerations when speculating about the timescale for completing the Step 3 part of the vision. The general considerations are that (i) we assume that it takes about 5 years to construct any significant machine once a proposal has been submitted, and (ii) a proposal is probably inappropriate before the FMC has been operating for 1 year, say.

5 Conclusions

We have described our current "vision" of the future evolution of the accelerator complex at Fermilab towards a site–filling high–energy high–luminosity 4 TeV muon collider. In this speculative look ahead the present facilities are enhanced with the addition of a muon storage ring neutrino source (Step 1), followed by the first muon collider (Step 2), and finally the 4 TeV muon collider (Step 3). The overall timescale to reach the 4 TeV goal is clearly long. Nevertheless, the muon collider vision has some very attractive features. It would enable Fermilab to retain a cutting–edge world class physics program over the next two decades, whilst maintaining a diverse capability, and significant flexibility to respond to new discoveries.

Acknowledgments

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Photograph Captions

Photograph 1: Schematic of the accelerator enclosures needed for Step 1. The target hall, decay channel, muon cooling channel, and acceleration systems are sited in a field near MiniBooNE. The stopped muon building is optional, depending on whether stopped muon physics is of sufficient interest to drive this addition to the program.

Photograph 2: Schematic of an alternative location for the accelerator enclosures needed for Step 1, with the target hall, decay channel, cooling channel, and acceleration systems installed in a long straight tunnel.

Photograph 3: Schematic of the accelerator enclosures needed for Step 2. RLA3 and the collider rings are located in the Dolomite layer below Fermilab. The μp collider is optional.

Photograph 4: Schematic of an alternative scheme for the accelerator enclosures needed for Step 2. All beam enclosures are near the surface. The μp collider is optional.

Photograph 5: Schematic of the accelerator enclosures needed for Step 3. The high energy accelerator complex and collider are constructed in tunnels within the Dolomite layer below Fermilab.